Flooding Data in a Cell: Is Cellular Multicast Better than Device-to-Device Communications?

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ABSTRACT

A natural method to disseminate popular data on cellular networks is to use multicast. Despite having clear advantages over unicast, multicast does not offer any kind of reliability and could result costly in terms of cellular resources in the case at least one of the destinations is at the edge of the cell (i.e., with poor radio conditions). In this paper, we show that, when content dissemination tolerates some delay, providing device-to-device communications over an orthogonal channel increases the efficiency of multicast, concurring also to offload part of the traffic from the infrastructure. Our evaluation simulates an LTE macro-cell with mobile receivers and reveals that the joint utilization of device-to-device communications and multicasting brings significant resource savings while increasing the cellular throughput.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Store and forward networks; Wireless communication;

Keywords

Cellular multicast; mobile data offloading; hybrid networks; delay-tolerant networks.

1. INTRODUCTION

With the deployment of increasingly performing cellular technologies, such as the 3GPP Long Term Evolution (LTE) and LTE-A, mobile networks will provide ever higher data rates (up to 100 Mbps for LTE, and 500 Mbps for LTE-A) [6]. Operators will exploit these opportunities to offer ubiquitous access to next generation services to their customers, such as multimedia applications, leading users to consume content anywhere, anytime. As a result, the expected mobile traffic will be very problematic to handle during peak times [5]. Among these multimedia services, some involve delivering the same piece of data to a community of interested users. Examples that fit this use case are software updates, on-demand videos, and road traffic information. When a multitude of co-located users are interested in the same content, two possible approaches could help operators to relieve their cellular infrastructures: *multicast* and *mobile data offloading*.

Multicast makes use of a single unidirectional link, shared among several users inside the radio cell, allowing, in principle, a more efficient use of network resources with respect to the case where each user is reached through dedicated bearers. Note that a more precise terminology would be "multicast/broadcast", because only a subset of nodes is concerned by the content (multicast), and the shared nature of the wireless medium (broadcast) is exploited to transmit data. For the sake of readability, in the following we will only employ the term "multicast". To ensure coexistence between multicast and unicast services, operators must reserve a fixed amount of resources for multicast transmissions. Lately, field trials for video service during crowded sport events like the superbowl have tested the effectiveness of multicast [8]. Despite its attractive features, multicast presents intrinsic and still unresolved issues that limit its exploitation due to the difficult adaptation to radio channel conditions. Section 2 will provide an example of these inefficiencies.

Mobile data offloading is an alternative low cost solution to reduce the burden on the infrastructure network [7, 3, 13]. Direct device-to-device (D2D) communications may be employed to lower the load on the infrastructure. The increase in the density of mobile users gives rise to an abundance of contact opportunities and represents a strong argument to support opportunistic offloading strategies. Not surprisingly, this has been identified as one of the key enabling technologies for future cellular network architecture [1]. In order to encourage subscribers to offer their battery and storage resources to this end, mobile providers may offer monetary incentives and pricing discounts. As a counterpart, users should accept a delayed content reception.

In this paper, *we explore the combination of opportunistic traffic offloading with multicasting.* As we will see later, this strategy allows significant reduction in the load on the access part of the cellular network. As standard multicast is not intended for retransmissions, performance suffers and resources are wasted in the case of a single bad channel user inside the cell, due to trade-offs in coverage and efficiency. By including D2D communications into the picture, we obtain additional performance gains in terms of radio resources. Well-positioned users participate in mitigating the inefficiencies of multicast, by sharing their short-range resources to hand over content to users in bad cellular channel conditions. Depending on the number of participants requesting data, we find a break-even point that achieves a good trade-off in terms of covered users and reception delay.

To assess the performance of this joint multicast/D2D approach it is necessary to evaluate the amount of radio resources consumed at the base station. This leads us to introduce a finer model of radio resource consumption than previous works in the offloading literature. Existing proposals do not consider heterogeneous channel conditions and assume that delivering a given amount of data to different users has always the same cost. Such an assumption does not hold in reality, as radio resources vary according to the channel condition experienced by each user. In other words, transmitting the same piece of content to users with different channel conditions do lead to uneven costs at the base station. To the best of our knowledge, we are the first to evaluate this aspect in the context of data offloading.

As a summary, the main contributions of this paper are:

- **Joint offloading strategy.** Our strategy employs direct D2D transmissions to assist the cellular distribution via multicast, permitting to consistently save resources at the cellular base stations.
- **Fine-grained resource consumption analysis.** We evaluate resource consumption employing the smallest radio resource unit that can be assigned to users for data transmission. This analysis shows that existing macroscopic techniques fail to capture actual system behaviors.

The remainder of the paper is organized as follows. We first present the motivation of our work in Section 2. The proposed joint offloading architecture and operation is described in Section 3. We evaluate the proposed system using realistic mobility traces in Section 4. We push the related work to Section 5 so that the reader has enough material to capture our original contribution. We finally conclude the paper and identify topics for future research in Section 6.

2. MOTIVATIONAL EXAMPLE

LTE proposes an optimized broadcast/multicast service through eMBMS (*enhanced Multimedia Broadcast Multimedia Service*), a point-to-multipoint specification to transmit control/data information from the cellular base station (eNB) to a group of user entities (UEs) [10].

Cellular UEs can use different modulation and coding schemes (MCS) to deal with variable channel characteristics. Each UE experiences different radio conditions, depending on path loss, interference from other cells, and wireless fading. UEs that are closer to the base station are able to decode data at a higher rate, while others located near the edge of the cell have to reduce their data rate and use a degraded MCS. This heterogeneity (time-varying and user-dependent) reduces the effectiveness of multicast because the eNB uses a single MCS to multicast downlink data. Usually, the selected MCS should be robust enough to ensure the successful reception and decoding of the data-frame for each recipient inside the cell. Thus, the worst channel among all the receivers dictates performance. An increase in the number of UEs boosts the probability that at least one UE experiences bad channel conditions, degrading the overall throughput [4].

To quantify this effect, we simulate a 500×500 m^2 single LTE cell with an increasing number of randomly located receivers using the ns-3 simulator [12]. Fig. 1 presents the average minimum channel quality, in terms of CQI (Channel Quality Indicator), reported at the eNB by UEs (static). The reported CQI is a number between 0 (worst) and 15 (best) as listed in Table 1. The CQI indicates the most efficient MCS giving a Block Error Rate (BLER) of 10% or less. We realize that the average minimum CQI value decreases as the number of users in the multicast group increases. The result is that augmenting the number of multicast receivers clearly impacts the attainable cell throughput. Table 1 shows that

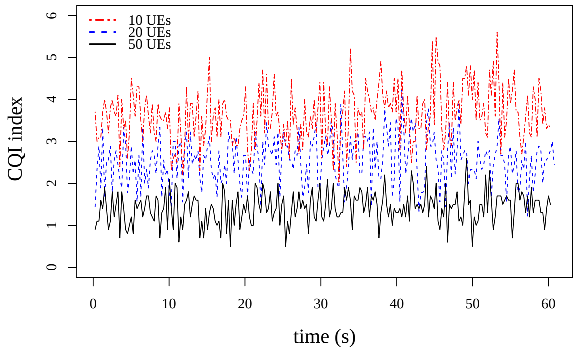


Figure 1: Minimum CQI for different multicast group sizes. 100 runs, confidence intervals are tight and not shown in figure.

Table 1: CQI / MCS Table for LTE [2].

CQI index	Modulation schema	code rate x 1024	Spectral Efficiency [bit/s/Hz]
0		out of range	
1	QPSK	78	0.1523
2	QPSK	120	0.2344
3	QPSK	193	0.3770
4	QPSK	308	0.6016
5	QPSK	449	0.8770
6	QPSK	602	1.1758
7	16-QAM	378	1.4766
8	16-QAM	490	1.9141
9	16-QAM	616	2.4063
10	64-QAM	466	2.7305
11	64-QAM	567	3.3223
12	64-QAM	666	3.9023
13	64-QAM	772	4.5234
14	64-QAM	873	5.1152
15	64-QAM	948	5.5547

a UE with the best CQI could theoretically receive 37 times the throughput of a UE with the lowest index.

This greatly motivates us to investigate methods to cope with the inefficiencies of multicast. We exploit the presence of alternative direct connectivity options available at UEs to relieve the cellular infrastructure load, while reducing the influence of UEs experiencing poor radio conditions.

3. JOINT D2D/MULTICAST OFFLOADING

We address the distribution of popular content to a set of N mobile UEs inside a single LTE cell. Each UE is a multi-homed device that embeds both an LTE interface and a short range wireless technology that allows D2D communications (we consider IEEE 802.11g in the paper). We want to transmit data to each UE with a guaranteed maximum *service delay* D at the minimum cost for the cellular infrastructure. In order to increase efficiency, we exploit D2D connectivity and store-and-carry forwarding. The challenging issue is that such a strategy is, by definition, unreliable, as it depends on many factors that are difficult to control (e.g., cellular channel quality, variable density of opportunistic neighbors, or interference on the D2D channel). To achieve guaranteed delivery, we consider an acknowledgment mechanism, and *panic zone* retransmissions similarly to [15]. When the service delay reaches its maximum value D, the eNB pushes all the missing data to uninfected nodes using unicast transmissions.

3.1 Cost function

What emerges from the analysis in Section 2 is that a UE with good channel quality can obtain higher bit-rates with the same amount of resource blocks (RBs), while bad channel users consume more RBs in order to transmit the same amount of data. To capture the allocation expenditure, we define the cost of transmitting to UE v_i as:

$$c(v_i, k, t) = \left\lceil \frac{s_k}{\mathcal{T}_{v_i(t)}} \right\rceil, \tag{1}$$

where s_k is the size in bytes of the k-th data block to be transmitted and $\mathcal{T}_{v_i(t)}$ is the transport block size (TBS) decided by the eNB. The cost function $c(v_i, k, t)$ measures the number of RBs needed to transmit a packet of length s_k to v_i at time t. In order to assign the MCS, and consequently $\mathcal{T}_{v_i(t)}$ (Table I, Tables 7.1.7.1-1, and 7.1.7.2.1-1 from [2]), the eNB uses the channel quality information obtained from the CQI messages that each mobile UE periodically transmits to the base station.[1]

3.2 Offloading strategy

The principles behind the joint multicast/D2D approach are: (1) at initial time, the eNB sends data to the I_0 UEs with the best radio conditions through a single multicast emission; (2) the UEs that have received the data (I_0 or less) start disseminating it in a D2D (epidemic) fashion; (3) before the maximum *service delay* D, we define a time interval, a *panic zone* where all the nodes that have not yet retrieved the content (either with the initial broadcast emission or in D2D fashion) receive it through unicast LTE emissions.

The proposed scheme allows all UEs to receive data by the deadline (as long as the panic zone is sufficiently large). It adapts to different *service delays* – the larger ones allowing for more D2D dissemination. Its performance relies essentially on one key parameter (I_0) that characterizes the number of UEs reached by the initial multicast transmission. Indeed, the eNB maintains a dynamic ranking of the UEs according to their instantaneous $c(v_i, k, t)$ values. By transmitting data with the MCS of the I_0-th ranked UE, the algorithm aims at reaching the best I_0 UEs in terms of channel quality. This immediately improves the usage of resources at the eNB, because it excludes the $N - I_0$ worst-channel UEs.

Fig. 2 offers a representative example of the proposed strategy with 6 UEs in the cell. Setting I_0=3, the eNB employs a MCS of 12 for the initial multicast emission. Thus, it reaches nodes with MCS of 12 and above, but leaves the three farther ones in outage (their MCS is 8). In the D2D dissemination phase, these *outaged* UEs benefit from nearby nodes, fetching data directly from them through out-of-band D2D transmissions. This cooperative strategy is by far more efficient in terms of cellular resource consumption than multicast alone, given that the transmission rate increases and the D2D links typically exploit a much larger bandwidth than cellular communications.

[1]The periodicity of CQI reports is comprised in the range $[2 - 160]$ ms in real LTE deployment.

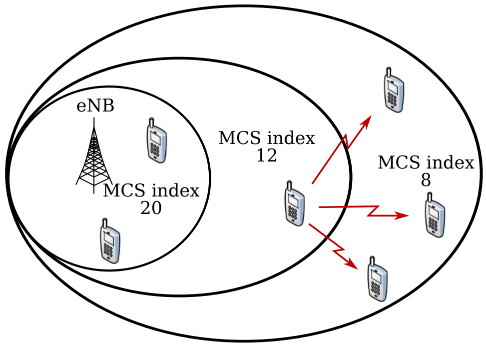


Figure 2: UEs can decode data with a maximum modulation schema depending on their position in the cell. The eNB may decide to multicast at higher rate (E.g., MCS index 12). UEs unable to decode data are reached through out-of-band D2D links.

Here resides the novelty of our approach: *the eNB trades off the set of recipients that minimizes the multicast cost on the cellular network, while guaranteeing full coverage through D2D communications and panic re-injections when needed.* Next, we will determine the best I_0 values with the aid of simulations for different scenarios of utilization.

4. PERFORMANCE EVALUATION

4.1 Methodology and parameters

We compare the performance of the proposed joint distribution system with the one achieved by the classic cellular multicast alone. All the results presented in this section are averages over 25 independent simulation runs. Standard multicast implementation transmits data to all the UEs inside the cell using the MCS allowed by the lowest reported CQI value. Even in that case, UEs have no assurance of reception. The radio channel could suddenly degrade during data reception (e.g., due to fast fading or mobility), preventing certain users to correctly decode data. For this reason, we consider an additional resilience layer in the form of panic zone retransmissions, which guarantee full dissemination at the cost of much higher resource consumption.

For now, we consider a static number of UEs within the cell for each simulation run, to prove the validity of the concept. Future work will tackle the case where UEs can enter and exit the distribution area. Node mobility is implemented according to the random way-point model with speed fixed at 27 m/s and pause-time set at 0.5 s. We simulate UDP constant bit-rate downlink flows, each one with packet size $s_k = 2048$ bytes and a total load of 8 Mb. We implemented our joint D2D/multicast strategy in the ns-3. Since ns-3 does not natively support cellular multicast, we implemented an additional module that interacts with the packet scheduler to emulate single-cell multicast. The multicast module receives the CQI reports of UEs and decides the transmission rate following the steps explained in Section 3. We fix the bandwidth allocated for the multicast service at 5 MHz. 3GPP standard recommends not to reserve more than 60% of RBs to multicast [10], so the 5 MHz value could represent respectively the 50% or the 25% of RBs in a typical 10 or 20 MHz deployment. Other simulation parameters for the LTE cell are listed in Table 2.

Parameter	Value
Cellular layout	Isolated cell, 1-sector
LTE downlink bandwidth	5 MHz (25 RBs)
Frequency band	1865 MHz (Band 3)
CQI scheme	Full Bandwidth
eNb TX-power	41 dBm
Pathloss	Cost 231
BS station height	30 m
UE station height	1.5 m
Fast fading	Extended Vehicular A (EVA) model
Multicast group size N	10, 25, 50 UEs
Service delay D	10, 30, 60, 90 s
% of direct recipients I_0	100 %, 70 %, 50 %, 30 %

Table 2: ns-3 simulation parameters.

Additionally, we implemented store-carry-forward routing mechanism at UEs to allow data forwarding on the WiFi interface. Regardless of its reception method, an unexpired packet can be forwarded on the WiFi interface upon meeting with neighbors. Neighbor discovery is implemented through a beaconing protocol. UEs periodically broadcast beacon messages containing their identifier and the list of buffered packets. Upon beacon reception UEs update their vicinity information and can decide to transmit a packet.

Implementation assumption: In simulation we make the following simplification:

- HARQ-level retransmissions and RLC-level feedback are disabled in multicast. This is a reasonable assumption: otherwise the eNB should merge the *ack/nack* messages received from all the UEs, and decide which is the best retransmission strategy. We guarantee data reception with *panic zone* retransmissions.

- The PUCCH channel is employed to acknowledge data reception towards the eNB. Panic zone retransmissions are then triggered looking at the list of received acknowledgments.

4.2 Reference strategies

No D2D is the basic strategy, where UEs have no direct connectivity options, and multicasting through the cellular infrastructure is the only means of distributing content. We compare this base case to our joint D2D/multicast strategy. We assess the performance for three different values of N – the number of users inside the cell – respectively 10, 25, and 50, so to evaluate performance under different loads. We also consider various values for the parameter I_0 – the number of direct multicast recipients. In order to be consistent with the notation, we evaluate this value as a percentage of N.

4.3 Evaluation

Reception Methods. UEs may receive packets concurrently on two interfaces, using three different reception methods: multicast and unicast on the cellular interface, D2D on the WiFi interface. Fig. 3 provides the fraction of packets partitioned by their reception method. For now, we focus only on their relative weight. As expected, the fraction of packets delivered through multicast follows I_0. The fraction of *panic zone* and D2D messages strongly depends on the parameters D and N. Tight service delays leave less time to opportunistic distribution to reach outaged UEs, resulting in a more intense use of panic retransmissions.

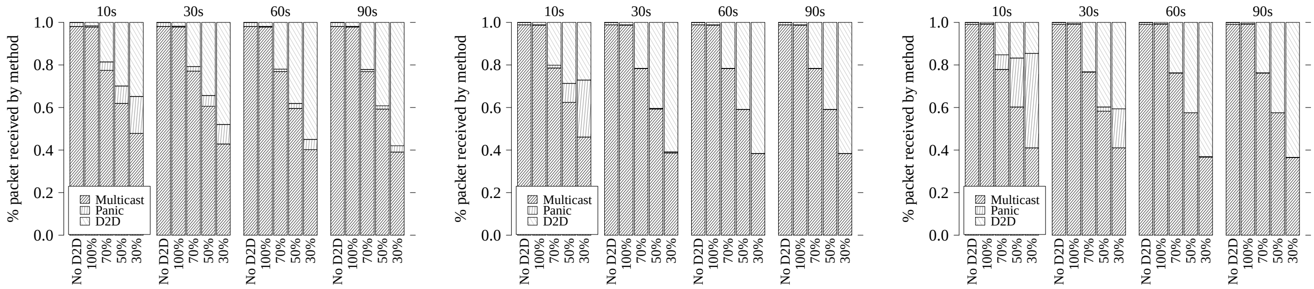
We can find a small amount of packet retransmitted during the *panic zone* even in the *No D2D* strategy. These are packets incorrectly decoded by UEs during the initial multicast emission. In the other strategies, D2D allows not to make use of retransmissions where possible, because UEs can retrieve missing packets from other UEs. For instance, the strategies *No D2D* and *100%* have the same fraction of multicast reception, but differ on the amount of panic and D2D messages. We note also that for sufficiently long *service delays*, *panic zone* is never triggered, and D2D transmissions meet the goal of guaranteeing total data diffusion. As we will show later this brings a lot of resource saving.

Cellular Resource Analysis. Mobile operators are primarily concerned about radio resource usage. Fig. 4 gives hints on the actual amount of RBs devoted to distribute data in the considered scenarios. Unlike previous figure, here we focus on the amount of consumed radio resources at the eNB.

The parameter N strongly affects the number of employed resources. This is even more evident if we consider very short *service delays*. While the amount of resources devoted to multicast only slightly increases with the number of UEs, the impact of unicast re-injections heavily depends on the number of UEs in the cell. This happens because N has a multiplier effect on unicast transmissions, and because with large probability uninfected UEs are the ones with the worst channel conditions. If we compare Fig. 3 and Fig. 4, it is impressive to note how in some cases a small fraction of unicast transmissions could translate into such a great resource usage. When N is large, the choice of good values of I_0 becomes fundamental in order to avoid congesting the cell with too many panic retransmissions.

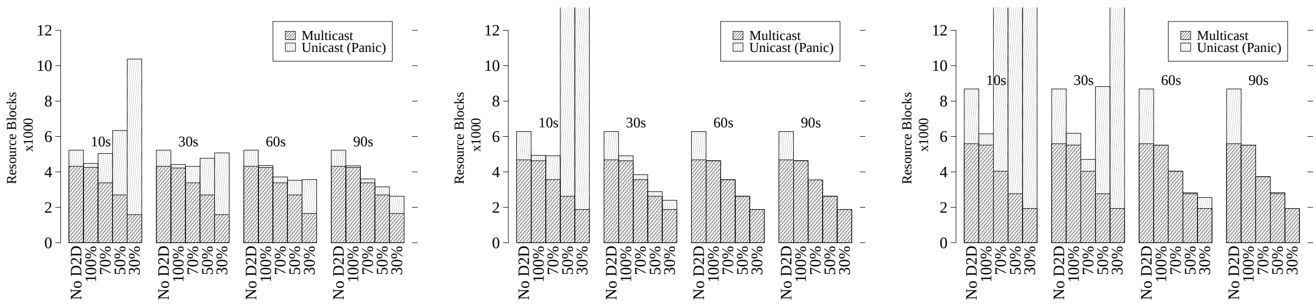
Another interesting result is that for any possible value of N and D, we may always find a joint D2D/multicast strategy that offers better results than *No D2D*. For low values of N and short delivery times, it is not possible to consider a great amount of outaged UEs, since opportunistic contacts between UEs are scarce, disallowing complete data dissemination before the expiration of the deadline. On the other hand, if we consider longer service times, and/or many UEs in the cell, simulation results tell us that it is possible to allow up to 70% of UEs in *outage*, reaching up to 3 times better resource efficiency. Note also that redundant multicast strategies with repeated retransmissions would never be optimal, since the amount of consumed resources would be more than double, without ensuring 100% data reception.

Cellular Rate The use of D2D communications increases the achievable data rate at the eNB. The proposed approach excludes from the set of direct multicast receivers the UEs in bad channel quality. These *outaged* users are reached opportunistically using D2D transmissions or through panic zone re-injections. In Fig. 5, we can evaluate the gain in terms of transport block size, with respect to the baseline *No D2D* strategy. An increase in the average TBS means that with the same amount of radio resources, the eNB can transmit more data. Average TBS is a mean to understand the quality of the cellular link connecting the eNB and the UEs. In general, the average TBS increases as I_0 decreases, since our strategy always serves the best placed UEs. This beneficial effect emerges if we look at the dashed curves (representing the TBS for multicast emissions only). However, the gain brought



(a) 10 UEs (b) 25 UEs (c) 50 UEs

Figure 3: Data packet ranked by reception method. *Multicast* and *Panic* flows through the cellular infrastructure, *D2D* is on the WiFi channel.



(a) 10 UEs (b) 25 UEs (c) 50 UEs

Figure 4: Average resource blocks employed at eNB to reach 100% dissemination. Note that even few panic zone retransmissions (in unicast) result very costly in resources.

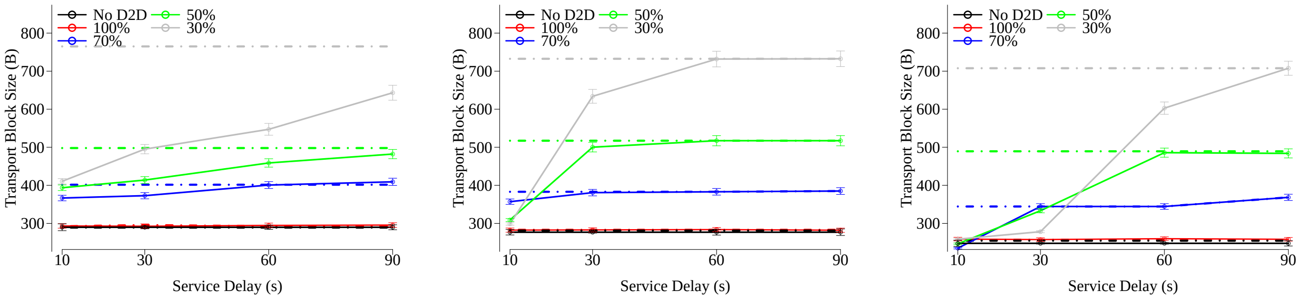
by the joint D2D/multicast strategy is often mitigated by the heavy use of panic zone re-injections to guarantee 100% data reception. This is the reason why the average TBS tends to saturate at the multicast value when the amount of panic retransmissions falls. For tight *service delays*, the opportunistic diffusion has not enough time to transfer all data packets to each UE. This forces the eNB to resort to panic unicast re-injections. The probability to have a bad channel is higher for the UEs that have not received the content, lowering the average TBS. For the *No D2D* and 100% strategies the penalty due to panic zone is negligible and never impacts the already low TBS in a noticeable manner. For larger maximum *service delay* the increase with respect to the conservative multicast-only strategy could be in the order of 2–3 times.

5. RELATED WORK

Mobile data offloading. D2D communications have been the target of intensive studies as a method to relieve the pressure on the cellular infrastructure. Typically only unicast transmissions are considered. For instance, Han et al. identified the opportunity to save infrastructure data exploiting the social ties between users, proposing a subset selection mechanism based on contact history [7]. Similarly, Li et al. analytically formulated the problem of traffic offloading of multiple contents in a mobile environment. Under the assumption of Poisson contact, the optimal subset selection problem is solved under multiple constraints [11]. Barbera et al. analyzed contacts between end-nodes in order to select a subset of socially important VIP users, which are turned into data forwarders [3]. We proposed a simple re-injection based scheme that takes into account the evolution of the opportunistic dissemination [13]. In all these works the principal metric is the amount of data (or messages) saved on the infrastructure link. While this is an influential driver for evaluation, it does not fully represent the real amount of saved resources at the base station.

D2D-aided multicast. Bhatia et al., proposed the use of D2D communications to improve performance of multicast in 3G cellular networks [4]. A multihop ad hoc network is modeled analytically. A near-optimal discovery algorithm selects the best data forwarder for receivers with poor channel quality. The authors in [16] devised an algorithm to figure out the optimal number of relays inside the cluster. The paper focuses on in-band D2D communications, such that considered in [1]. Similarly, in [14], only the cluster head receives the content and is in charge of D2D retransmission inside its cluster. No hints are given on how clusters are created and discovered. Huo et al., proposed a cooperative multicast scheduling for 802.16 networks. A two phase schema is proposed, and all successful recipients of multicast participate in data retransmission using in-band D2D links [9].

6. DISCUSSION AND PERSPECTIVES



(a) 10 UEs

(b) 25 UEs

(c) 50 UEs

Figure 5: Average transport block size for different *service delays*. Solid lines show the average (multicast + unicast), dashed lines display only multicast.

In this work, we have presented a hybrid distribution system for popular content with guaranteed delays. Multicast is a valuable option to distribute popular data into a cellular network. However, performance is limited by the channel quality of the worst UE in the cell. We proposed a framework that exploits D2D capabilities at UEs to counter the inefficiencies of cellular multicast. We evaluated the performance of a joint D2D/multicast strategy by varying the number of UEs in the cell and the maximum reception deadline. Simulation results prove that the use of D2D communications allows increasing the multicast transmission rate, saving resources and improving the overall cell throughput.

Future work will focus on the development of analytical models for epidemic data diffusion to aid the choice of which UEs to insert in the set of direct multicast recipients. Moreover, we will evaluate the scenario where multiple neighboring cells are active, and UEs can roam between them.

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Filippo Rebecchi and Marcelo Dias de Amorim carried out part of the work at LINCS (http://www.lincs.fr). This work is partially supported by the European Commission in the framework of the FP7 Mobile Opportunistic Traffic Offloading (MOTO) project under grant agreement number 317959.

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